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**Glacial landscape architecture and sediment sampling, Mary
Frances Lake – Whitefish Lake – Thelon River area (NTS
75-I, 75-J, 75-O, 75-P), Northwest Territories, Canada**

**D.R. Sharpe, J-E. Lesemann, R.D. Knight,
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1.0 Introduction

This report presents a preliminary analysis of the glaciated terrain and surficial sediment in support of a mineral exploration investigation in the headwaters of Thelon River, Northwest Territories. Approximately 180 sediment samples were collected in July 2012 in a study area bounded by Mary Frances Lake and Whitefish Lake (to the west) and the Thelon River to the east ([Fig. 1](#)). The area lies to the southwest of the Thelon Wildlife Sanctuary, east of the area of interest for Thaidene Nene ([Fig. 1](#)), and encompasses ~3,500 km² (parts of NTS 75-I, 75-J, 75-O, 75-P).

Few government geoscience activities have been undertaken in the study area. The earliest work consists of geological investigations by J.B. Tyrell (Tyrell, 1896), and surveying with minor geology by J.W. Tyrell (Tyrell, 1902). Bedrock geology and surficial sediment were subsequently not systematically examined until Operation Keewatin (Lord, 1953, Wright, 1957, Craig, 1964; Wright, 1967), with updating by Kjarsgaard et al. (2013) and Pehrsson et al. (2014). Bedrock geology is currently mapped at 1:1 000 000 scale ([Fig. 2](#)), with more detailed mapping associated with uranium exploration in selected areas (e.g., Davidson and Gandhi, 1989; Jefferson et al., 2011). The regional surficial geology was compiled by Prest, 1970; Prest et al., (1968), and in greater detail by Aylsworth and Shilts (1989a, b, c) ([Fig. 3](#)). Several recent studies have been conducted east of the Thelon sedimentary basin ([Fig. 4](#); e.g. McMartin and Henderson, 2004), and for resource assessment purposes in the region of the East Arm of Great Slave Lake (Kjarsgaard et al., 2013a; Kerr et al., 2013; Sharpe et al., 2013). In addition, a number of non-governmental mapping and process-focused studies of landforms and land systems have been carried out in regions encompassing the present study area (e.g., Stokes et al., 2002, 2003a, b, 2006, 2013; Tulaczyk et al., 2007; Shaw et al., 2010).

1.1 Landscape architecture

Glacial terrains consist of complex assemblages of landforms and sediments (land systems). They are the product of poorly-understood processes of erosion, transport and deposition of bedrock and sediment, containing lithologic, heavy mineral and geochemical characteristics of interest (e.g. Hooke et al., 2013). In order to unravel transport patterns, the landscape architecture needs to be described in precise terms that can be related to contributing formative processes. In the study area, landform types and patterns are intricate and variable. This variability forms regional landscape patterns and transitions (e.g., spatial and form changes from ribbed moraine to streamlined terrain; Aylsworth, and Shilts, 1989a), which are marked by more detailed terrain features and elements (Sharpe et al., 2013a). Ideally, local terrain features can be linked to landscape architecture at different scales so as to guide sample design and analysis in landscape complexity.

1.2 Purpose of the Report

The purpose of this report is to describe and illustrate the main glacial terrain elements (landscape architecture) and related character of the surficial sediment in the study area. We then assess their significance in terms of mineral exploration sampling strategies, and preliminary interpretation of results.

Sampling for geochemical surveys in glaciated terrains has traditionally focused on till as a sampling medium (e.g. McMartin and Campbell, 2009; McMartin and Paulen, 2011; Paulen and McClengahan, 2013), with limited use of process models and regional landscape elements to constrain the interpretive framework of these results. However, landscape architecture is potentially significant in designing sediment sample surveys and in interpreting sediment dispersal (geochemical, boulder and indicator mineral tracing) results for mineral exploration (e.g. Salonen, 1987; Liverman and Vatcher, 1992; Rampton, 2000).

This study was designed to maximize the use of regional-scale landscape architectural elements in the sampling process and interpretive framework of results. Thus, we present results from one of the first examples of a combined regional-scale till and esker sampling strategy (see also Kjarsgaard et al., 2013b). The interpretive framework of results is bolstered by incorporating complex and variable terrain elements in interpretations of erosional and depositional events. This approach is used as a guideline to improve future mineral exploration methods in glaciated terrains.

2.0 Detailed methods

2.1 Sample design and collection protocols

Surficial sediment samples were collected by helicopter traverses in July 2012 (181 samples) and consisted of 76 esker samples and 105 diamicton samples ([Fig. 5](#)). Esker samples were taken every ~10 km along each esker ridge-line. Diamicton (till) was sampled every ~100 km², based on a 10 km x 10 km grid. At each till site, a 15 kg heavy mineral sample, a 1 kg geochemical sample, 50 pebbles, and a 100 g pXRF sample were taken for analysis. Samples were taken by digging pits up to 1 meter deep. Sediment stratigraphy was recorded in each pit. Samples were collected at depths well below any active layer cryoturbation in the top of the pit (<50 cm). Any near-surface reworking above the sample target, diamicton (till) or esker (glaciofluvial) sand was noted in the pit stratigraphy. The terrain context was noted for all samples collected including terrain elements such as, drumlin, corridor, terrace and esker.

The sampling design and density replicates the protocol developed and used for the Thaidene Nene MERA mineral potential study to the east of the study area (Kjarsgaard et al., 2013b). Each sample site was photographed (sample pit, surface sediment, terrain context, landform and paleoflow indicators). Paleoflow indicators (e.g., striations, s-forms, streamlined landform) were measured along the axis of the landform, and/or where bedrock was present adjacent to the sampling site (~100 sites). Standardized information about the

sediment and the sampling site was digitally recorded on a Trimble Yuma field computer utilizing a custom-designed database entry form. The co-ordinates of all samples were captured with a hand-held global positioning system (GPS).

A standardized site photography protocol was established to document sampling sites and surroundings. Sample site photos were used to document the surface and sampled material. These include: i) sample hole and sediment, ii) sampling site, iii) sampling site background. The landform and landscape context of each sample site was documented by photography of: i) surrounding landforms and morphologic variability (~10s-100s m), ii) terrain in four cardinal directions (N-S-E-W), iii) oblique aerial perspectives from helicopter taken during arrival and/or exit from sampling sites. Two teams sampling in tandem allowed for maximum terrain coverage and use of helicopter time and fuel. All analytical results for indicator minerals, till geochemistry, and pXRF spectrometry are presented separately (Knight et al, 2013; Kjarsgaard et al., 2013c; Plourde et al., 2013, respectively).

Terrain analysis is based on examination of SPOT panchromatic, LANDSAT ETM and black and white aerial photographs, in part used to generate a remote predictive map (RPM) of surface materials and terrain features. Ground controls consist of ~2000 km of low-level helicopter and fixed-wing viewing and photography (>5,000 GPS-fixed images), and detailed study at the 181 sampling sites. Terrain analysis identified the key glacial, glacial-fluvial and post-glacial landforms and sediments that may affect sediment dispersal patterns. Terrain ground control was linked to the RPM product and imagery.

3.0 Surficial Geology

3.1 Regional landscape setting

The study area lies in the Keewatin Sector of the former Laurentide Ice Sheet (LIS), west of the Keewatin Ice Divide (Fig. 4; KID; Lee et al., 1957; Dyke and Prest, 1987). Glacial bedforms in the region (*e.g.* eskers, ribbed moraine, streamlined landforms) have been interpreted as depositional landforms and form a broad, regionally-radial, concentric, zonal pattern around the former Keewatin Ice Divide (Shilts et al., 1987; Aylsworth and Shilts, 1989a,b,c). Till and sand of varying total thickness (~1-50 m) are dominant sediments within the study area. Terrain relief is low (1-50 m) and consists of plains and E-W trending undulating hills parallel to regional flow from KID west to Great Slave Lake (Prest et al., 1968; Shaw et al., 2010). A large (10s to many 100s km length) E-W-trending esker array occurs within the regional undulating plains (Craig, 1964).

3.2 Regional features and landscape models described in the literature

Reconnaissance field-work in the area, as part of Operation Keewatin (Lee in Lord, 1953; Fyles in Wright, 1955; Craig, 1964), revealed a variety of both small and large landforms. The most common small forms reported were *roches moutonnées*; less common were smooth rock knobs, some with stoss or lee-side sediment ridges, crag-and-tail, and poorly preserved striae. Larger features, drumlins and fluting are common yet occur in wide

variation of forms. Drumlins show a slightly divergent east to west pattern across the area (Fig. 3). Low relief drumlins are present to the east of the Thelon River with forms delineated by differences in the type and moisture content of vegetation on aerial photographs (Lee, 1959). A few drumlins have terraces along their sides, in places there may be three or four parallel scarps. Transverse ridges, with boulder-covered ridge-tops occur at right angles to drumlin long axes (Craig, 1964). Most drumlin surfaces consist of sandy diamicton with boulders, while some contain medium sand with a few boulders (e.g. exposed drumlin south of Garde Lake, see Craig, 1964). Till has been reported widely across the region. Craig (1964) described a prominent regional esker network and ice flow patterns extending from the Thelon River westward to southern Slave province, in excess of 250 km in length. They also show a slightly divergent east to west pattern across the area (Fig. 3). Meltwater appears to have scoured sediment from rock surfaces along prominent esker paths and adjacent to esker ridges according to Craig (1964; also see his plate VII). Till and esker sediment in the study area is sandy with the sand being quartz-rich, derived from quartz sandstone source rocks in the Thelon Basin to the east (Kjarsgaard et al., 2013c, 2014).

A model of glacial landscape formation was developed by Fyles (in Wright, 1955) and Craig (1964) during Operation Keewatin. This was one of a series of reconnaissance geologic assessments of the Keewatin and adjacent districts (e.g., Lord, 1953; Wright, 1957, 1967) that used air photo, helicopter and fixed-wing aircraft surveys to produce synoptic surficial maps and reports of a vast glaciated landscape, not systematically studied previously except along river traverses (e.g., Tyrell, 1896; Taylor, 1956). In the Fyles-Craig conceptual model of the Keewatin-Mackenzie glacial terrain, drumlins and related directional features are considered to have been deposited near the ice-margin, parallel to the direction of late ice movement. This hypothesis implies sequential step-wise landform construction (sediment transport and deposition) during a general retreat-phase of the ice sheet (possibly during or close to deglaciation). However, new field observations described here do not support this long-standing conceptual morphogenetic model. We provide an alternative and more robust model for glacial landscape evolution, and utilize this information to assess implications for mineral and geochemical dispersal patterns.

3.3 Forms and features in the Thelon study area

Both bedrock and sediment landforms are prominent on a regional-scale (Figs. 6, 7) and are illustrated in a summary sketch to aid in their description and their co-relationship (Fig. 7).

3.3.1 Erosional features in bedrock

Erosional features in bedrock occur at a range of scales and define a slightly divergent east to west flow pattern with some indication of southwest flow (Fig. 6). Forms consist of striations, small grooves, whalebacks, *roches moutonnées*, sculpted forms (s-forms) as well as bedrock exposed corridors that can be flanked by bedrock platform, escarpment, and that may be transitional to more clearly incised bedrock channels (Fig. 8).

Large sediment-free areas consisting of bedrock platform (Fig. 8) occur either along the floors of bedrock exposed corridors, or outside these corridors as slightly upstanding areas surrounded by depressions or lower zones of thicker, semi-continuous sediment cover. In some cases, bedrock platforms flank bedrock channels (Figs. 8, 9) to form km²-scale areas of exposed rock surfaces. On bedrock platforms, sediment (<1 m thick) may be present in the lee of protrusions (Figs. 8, 10). Aerial coverage of such sediment patches is subordinate to surface exposure of bedrock.

The morphology of bedrock platforms is variable. These surfaces are frequently smooth and contain grooves ('furrows') (Figs. 8, 10) with undulating surfaces (Fig. 11) that exhibit very few striae (Fig. 12). Furrows can be 10s of cm in width and up to a few meters in length. In places, outcrop expanses exhibit 1-10 m scale 'whaleback' features (Fig. 11, 13) *roche moutonnées* (Fig. 14) and moderately-developed sculpted s-forms (Fig. 15) that can be used as directional indicators. Note that 'whaleback' forms have smooth, rounded lee-side surfaces (Figs. 13, 15), while *roche moutonnées* have ragged lee-side surfaces (Fig. 14); most of these rock forms carry boulder concentrations on or adjacent to their surfaces (Fig. 16). Crag and tail (Fig. 17) forms occur on the margins of, and in places within, bedrock platforms.

Bedrock channels of various scales are associated with bedrock platforms (Fig. 8). 'Large' channels (many 100's m to kilometers in length) may bisect bedrock platforms (Fig. 9). These channels commonly have box-shaped cross-sections and may be eroded as much as 50 m below the platform. 'Large' channels may contain over-deepenings (containing lakes) along their length (Fig. 18), in areas where channels are in or extend beyond the platform. Escarpments flanking rock platforms sometimes exhibit networks of crescentic depressions or sinuous depressions (with lakes) on the stoss side and flanks of escarpments. Small sediment patches are observed on bedrock surfaces at the top and in the lee of these escarpments (Fig. 10).

'Small' channels (10s-100s m length-scale) are eroded within bedrock platforms but do not typically bisect these surfaces (Fig. 8). They are clustered within smoothed interfluvial areas and carry s-forms (Figs. 19, 20). All scales of channels likely exploit pre-existing bedrock joints or other structural elements.

3.3.2 *Drumlins and related streamlined forms in sediment*

Streamlined forms are widespread in the study area (Fig. 21) and include drumlins, flutings, and crag-and-tails. Often these forms are arranged in large fields covering 100s – 1000's of square kilometers; some forms are 1-3 km long, 100-250 m wide and 5-40 m in height. Streamlined forms are frequently highlighted by prominent vegetation bands (Figs. 21, 22) as noted east of the area by Lee (1959). These forms vary from asymmetric to symmetric. Asymmetric forms exhibit wide and steep stoss-sides and taper in height and width down flow (Fig. 21). Crescentic lakes are visible up flow of many streamlined forms (Fig. 22). Within a field, drumlins can occur as isolated forms with well-defined troughs between neighboring drumlins (Figs. 21, 22). In other cases, drumlins occur in groups arranged within an area of topographic high (Fig. 21) and often resemble 'shield' drumlins (e.g., Shaw (1983). Within shields, stoss-side troughs and inter-drumlin areas

(low flanks extending laterally between neighboring drumlins) occur at variable elevations (Fig. 23). Inter-drumlin areas can be linked by benches, highlighted by colour bands on drumlin flanks, occurring at elevations slightly above those of the stoss-side trough (Figs. 21, 22, 23). In such cases, the stoss-side trough commonly exhibits terraces (Fig. 23) that can be traced laterally along the flanks and may grade into an inter-drumlin bench connecting neighbouring drumlins.

Clear erosional features such as sculpted banks (forming incipient terraces?) (Fig. 22, 24), truncated flanks (Fig. 25) with stone concentrations (Fig. 26), and scours are common on the stoss-side of drumlins. Depressions formed by linked stoss-side troughs, can form a series of arcuate crescentic lakes extending across multiple drumlins, flanked by furrows, terraces and sculpted banks (Fig. 27). As well, linked stoss-side troughs can extend as depressions, furrows, parallel to drumlins (Fig. 27) to form prominent channels (15-100s m wide and up to kilometers in length) eroded through inter-drumlin areas (Fig. 22). Stone concentrations are common on most drumlin surfaces (Fig. 28): on stoss-sides (Fig. 29), on flanks immediately below the crest (Fig. 30), and, near the tail as it tapers leeward (Figs. 26, 28). The highest concentrations of boulders and often the largest clasts in this landscape occur on drumlin stoss sides (Fig. 29).

Drumlins occur in association with thin sediment and exposed rock in inter-drumlin terrain. In thin sediment areas, drumlins are low relief, 5-15 m high (Fig. 31). Drumlins also occur in association with long corridors that truncate drumlin fields (Fig. 31). S-forms and faint striae (Figs. 12, 19, 20) may occur on rock ridges in both inter-drumlin and corridor settings. Boulders, cobbles, and pebble concentrations occur on thin sediment in the lee of rock outcrops (Fig. 32), on rock surfaces in inter-drumlin areas (Fig. 28), and in corridor settings (Fig. 31).

Although drumlins occur primarily in sediment, streamlined rock forms also occur. In addition, this terrain contains crag and tail forms, where a streamlined bedrock crag (Fig. 17), or bedrock plateau (Fig. 8) is often associated with a down-flow sediment tail (Fig. 10). Crag and tail forms have boulders on upflow outcrops and a stone concentration along their trailing ridges (Fig. 17).

A stone-poor, fine, sandy diamicton, < 5 m thick, is often observed on drumlin surfaces. In drumlins exceeding 10m height, measured stratigraphic sections reveal 10-30 m thick, fine sandy beds below a carapace of diamicton (Figs. 25, 33). Drumlin form (outer surface) truncates the diamicton carapace and the horizontal sandy beds beneath it, as observed at two sites including, i) a drumlin flank (Fig. 33), and ii), drumlin stoss ends (Fig. 25, sandy area). Many sand-cored drumlins can be identified across the landscape by the prominent gullies eroded into their flanks (e.g., Figs. 25, 33).

3.3.3 Terraces

Terraces are common on drumlin flanks and may surround most of the form (Figs. 21, 23, 24, 25, 27). Terraces may be coincident with corridor margins where they are well-defined (Fig. 31). They occur as single or multiple benches 10-50 m wide (Fig. 33), often becoming wider downflow. Stone concentrations on their surfaces comprise rounded

cobbles and boulders that entirely cover underlying diamicton (Figs. 30, 32). This stone layer is often coarser on the stoss-side and fines along the landform axis where it may display bar forms with well-sorted, rounded gravel (Fig. 34) and scour pits around the boulders (Fig. 35). Terraces may also show surfaces of reworked diamicton with a mix of rounded to sub-rounded and sub-angular clasts, in a loose sandy matrix with little silt.

3.3.4 Corridors

Corridors form numerous broad zones across the landscape with exposed bedrock within, and thicker drumlinized sediment (>10 m) outside, the corridor (Figs. 7, 31). Corridors truncate drumlins and are inset with eskers (Fig. 31). They are most clearly defined as 1-3 km-wide sediment-poor areas where large eskers are inset (Fig. 31). Corridor margins are abrupt where they truncate or cut across continuous drumlin field (Fig. 31). Corridor margins are vague where there is little if any landform truncation (Fig. 27). Corridors also erode drumlins in the form of small scours, banks, terraces and channels (Figs. 22-25, 36) leaving stone concentrations (Fig. 16, 26, 32).

Scoured bedrock and thin remnant till with scattered boulders occur on corridor floors (Fig. 32). Bedrock expanses (Fig. 8) with sediment-free areas also define corridors. These rock expanses are scoured, contain furrows and undulate with smooth 'whalebacks', *roche moutonnées* and sculpted forms (Fig. 10). Smoothed rock surfaces may exhibit fine striae (Fig. 12) and s-forms (Fig. 20). Other corridor segments may contain till veneer with stone concentrations (Fig. 16), gravel blankets (Figs. 30, 34), bars (Fig. 37), and transverse ridges (Fig. 38).

3.3.5 Eskers / hummocks

At the synoptic scale, eskers form a regular east-west trending pattern of ridges (Fig. 3), radiating westward from the edge of the Keewatin Ice Divide (Lee, 1959). Within this radial pattern, esker spacing is consistently 8 to 10 km (Fig. 39). Eskers can be traced for more than 200+ km across the area with unbroken segments up to many 10's km long, connected by areas of hummocky sand and gravel, or zones of sediment-free bedrock expanses (corridors) (Fig. 31). The main esker ridges occur parallel to the synoptic ice sheet flow direction inferred from streamlined landforms (Figs. 3, 39).

Wilson (1939) and Craig (1964) described eskers in this area as being 'railway-embankment' type, presumably referring to single crest, "flat-topped" eskers (Fig. 40). However, the regional assessment of esker morphology and their association with other landforms undertaken in this study area reveals a complex array of esker types and morphologies (Fig. 41). Esker ridges range from 5-35 m high with a variety of geometries; they can be single, sharp-crested (Fig. 42) or multi-crested (Fig. 41), the latter consisting of either single or multiple bifurcations and re-attachments (Fig. 43). Single bifurcations occur over a few 100s meters in extent. Multi-bifurcation creates an anabranching esker pattern extending laterally over many 100's of meters (Fig. 43) and up to a few km in a downflow direction.

Many esker segments exhibit lateral sediment aprons composed mainly of sand (Fig. 41, 40). Closed depressions also occur within these lateral aprons. These closed depressions are frequently associated with bifurcating eskers and can define diverging ridges by accentuating the inter-ridge lows (Fig. 43). The depressions have limited sediment fills and are frequently 10's m deep; some are as deep as the esker ridges are high. In places, small isolated mounds or hummocks of sand and gravel, 3-8 m high, may occur adjacent to main esker ridges. In other places, esker ridge(s) grade downflow into broader plain-like areas composed mainly of sand (Fig. 41). These sand plains frequently contain closed depressions and hummocky surfaces. In places, the plain surface appears streamlined. Hummocky plain surfaces trend laterally toward drumlinized surfaces (Fig. 41). Hummocks and aprons may be more extensive in places (Fig. 44), though they appear to be bounded within corridor sides (Figs. 41, 44).

Esker ridge profiles are also variable across the region. Both single and multi-crested eskers can be either sharp-crested or flat-topped (Fig. 45). Sharp-crested eskers typically have an undulating longitudinal ridge (Fig. 42) where high points along the ridge correspond to more gravel and frequently exhibit exposed cobbles and boulders at the surface. Low points along esker ridges are sand-rich with varying amounts of gravel. Flat-topped eskers occur as kilometers-long, sand-dominated segments up to ~100 m wide (Fig. 41), where the surface is gently undulating or featureless. Flat-topped segments commonly grade laterally into sand aprons on the esker flanks (Fig. 41), especially where flat-topped ridges coincide with topographic low points along the esker. In other cases, flat-topped eskers exhibit braided paleo-channels across their surface. Braided esker tops sometimes grade to low relief sandy braidplains (Fig. 46). An individual esker (or esker segments that can be linked along a continuous path) may exhibit many or all of the morphologic elements described above.

3.3.6 *Transverse ridges*

Transverse ridges comprise gravelly features ~20-50 m long, 5-15 m wide and 2-5 m high (Fig. 38). They occur on or near scoured bedrock surfaces with limited sediment and within bedrock corridors. These ridges are prominent adjacent to eskers in the northwest corner of the study area (Fig. 3), and were originally noted by Craig (1964).

3.3.7 *Strandlines*

Occasionally multiple, parallel bench-like ridges occur on drumlins and other local topographic highs. In places these bench-like ridges display spit-like extremities (Fig. 47) and are identified as shorelines by Lee, in Lord (1953) and by Craig (1964). Sub-rounded gravel clasts occur on the ridge surface (Fig. 48). Clasts do not appear to be shingled or imbricated on concentric ridges, though the local diamicton is stone-poor. Few, if any, of these bench-like ridges occur on eskers. There may be some similarities between linear ridge segments and terraces found on some drumlins as both have sand /gravel concentrations. These ridges are most prominent near escarpments just west of Thelon River (Figs. 3, 47), as noted by Craig (1964).

Craig mapped features west of the study area at ~395 m asl that he considered linked to eastward retreat of the ice margin to form glacial Lake Thelon at ~380 m asl; potential

strandline features occur at ~350 m asl in the north-trending part of the Thelon Valley (Fig. 3). Craig also considered much of the sediment, largely gravel with Thelon derived sandstone, on terraces along valley sides and around uplands as shoreline sediments. However, no fine-grained (i.e., lacustrine) deposits, and only a few small deltas composed of sand were noted by Craig (1964).

3.3.8 Periglacial/ permafrost features

A number of periglacial/ permafrost related features such as patterned ground, are present in the study area as it is north of the treeline and within the area of extensive discontinuous permafrost (National Resources Canada, 1995). Large, 30-50 m diameter polygons (Fig. 49), and mud-boils (Fig. 51) are common. Less common are solifluction lobes on sloped surfaces (Fig. 50).

3.4 Terrain elements and sediment sampling

All 181 sediment samples were collected from the described terrain elements: drumlins, corridors, terraces and eskers. The sample design provides data as to how sediment (boulders, mineral indicators, and trace elements) are dispersed across the various terrain elements. Diamicton, a non-sorted silty-sand, was sampled in a number of terrain elements, while sorted (glaciofluvial) sand was sampled only from eskers. Diamicton sample pits, 50-80 cm deep (Fig. 51), revealed the following typical sequence in a corridor setting: a) 0-25 cm of loose, sub-rounded, pebbly, cobble sand over; b) 30-55cm of compact pebbly, silty fine sand diamicton. Most sites have more stones on the surface (~5-10%) than are present within sampled diamicton (~3%) (Figs. 51, 52). This concentration of rounded to sub-rounded gravelly sediment was observed on the surface of corridors, drumlins, terraces and eroded banks compared to the lower abundance of clasts from sediment obtained from the sample pits (Fig. 52).

Where sampled, diamicton contains angular to sub-angular, striated clasts (Fig. 53) with a compact matrix of fine sand and silt. Diamicton was sampled from within subglacial landforms, drumlins, or from till veneer found directly (<1 m) on top of bedrock. At a number of sites, there is a 0-25 cm zone of periglacially-reworked sediment above the sampled diamicton; or, in places, a new depositional unit, gravel, was found (Fig. 54). Some of this surface sediment is well-sorted, rounded gravel that occurs as bar forms (Fig. 37); these forms show grading of sediment size from large to smaller clasts in a downflow direction (Figs. 30, 34, 37). Scour pits (Fig. 35) may be observed around very large boulders, positioned flow-parallel to corridor direction. The overall context and sediment characteristics indicate that these diamicton surfaces were reworked by one or more of glaciofluvial deposition, shoreline processes, or by frost-sorting processes.

4.0 Interpretation

4.1 Conceptual Terrain model

A sketch of the key landscape elements based on field observations is depicted in [Figure 7](#). This conceptual landscape model provides an interpretive framework highlighting erosion forms on rock, bedrock channels at multiple scales, drumlins, sculpted banks, corridors, terraces, eskers, hummocks, transverse ridges as well as till veneer and glaciofluvial sediment of variable thicknesses.

4.2 Sampled sediment

Diamicton at most sites is interpreted to be a till; and is common across the landscape. This till comprises of angular to sub-angular, striated clasts ([Figs. 52, 53](#)) with a loose to compact matrix of fine sand and silt within subglacial landforms, drumlins, or where till was deposited directly on top of eroded bedrock. At most sites the 0-25cm zone of sediment above the sampled diamicton (till) ([Fig. 54](#)) is considered to be glaciofluvially reworked till, or glaciofluvial deposits (e.g., Rampton, 2000), which sometimes exhibit evidence of periglacial activity. Reworking, to some extent, however also occurs in the active layer of permafrost due to solifluction ([Fig. 50](#)) and to cryoturbation in mud boils and in ice-wedge polygons.

Glaciofluvially-reworked till is interpreted for sites with a mix of rounded to sub-rounded and sub-angular clasts ([Fig. 53](#)), in a loose sandy matrix with little silt. Glaciofluvial deposits however, consist of well-sorted, rounded gravel that occurs in bar or terrace forms ([Fig. 53](#)); these settings display a grading of clast size from large to smaller in a downflow direction ([Figs. 30, 34](#)). At some sites in the eastern part of the study area the reworked sediment represents shorelines ([Fig. 47](#)) comprises glaciofluvially-rounded clasts and or washed till. At some sites solifluction re-distribution may have occurred ([Fig. 50](#)), although care was taken to avoid sampling in these disturbed sediment areas. Mud (frost) boils were explicitly targeted for sampling, where thin sediment occurred and because of the association of mud boils with matrix sediment in diamicton (till). For mudboils sediment was sampled at depths of 60-80 cm avoided active layer cryoturbation at ~20-40 cm depth.

The lithology of transported sediment has an important impact on using sediment sampling for mineral exploration. Till and esker sediment in the study area is rich in quartz sand, derived from quartz-rich sandstone rocks in the Thelon Basin to the east (Kjarsgaard et al., 2013c, 2014, as well as granitic lithologies across the Rae domain ([Fig. 2](#)).

4.3 Bedrock erosion forms

Sediment-poor surfaces that form bedrock expanses can be interpreted as areas of non-deposition, or areas where sediment has been eroded following deposition. Multiple lines of evidence from this study favour an erosion model for these areas, as evidenced by:

- (1) The occurrence of sediment patches in the lee of bedrock obstacles ([Figs. 8, 10](#)) at various scales ([Fig. 17](#)) suggests protection of sediment in sheltered areas.
- (2) Boulder concentrations on rock and thin till surfaces ([Fig. 16](#)) suggest that these clasts represent lags following removal of finer-grained sediment. Note that ice is poor at sorting (Alley et al., 2007) and is unlikely to solely deposit boulders, particularly rounded boulders.
- (3) Bedrock channels (at multiple scales), s-forms, and morphologic elements associated with flow separation around bed obstacles (crescentic troughs, lateral furrows, e.g., Kor et al., 1991) represent glaciofluvial forms rather than ice-related features. Multiple lines of evidence indicate that bedrock expanses, with superimposed smaller erosion forms and boulder lags, likely record removal of sediment by meltwater.

4.4 Erosional meltwater corridors: esker corridor

Sediment-poor corridors ([Fig. 31](#)) with scoured bedrock, thin till, and scattered boulders are interpreted to be meltwater erosion paths. Meltwater in these corridors eroded till and rock formed scours, sculpted banks/slopes, drumlin margins and terraces as channels ([Figs. 23-25](#)) and stone concentrations ([Fig. 26](#)), leaving stone concentrations on the landforms as lags ([Figs. 16, 32](#)). Eskers, (a depositional feature), are inset within the erosional corridors and thus must post-date the erosion of the corridors ([Fig. 31](#)). Given that most eskers are subglacial deposits (Brennand, 2000); this implies that the erosional corridors must also be of subglacial origin. Hence, this landform setting of subglacial meltwater corridors, is the equivalent of tunnel (subglacial) valleys that have been extensively mapped in thick sediment areas of southern Canada (e.g., Brennand and Shaw, 1994; Brennand et al., 2006; Sharpe et al., 2013a, b). We extend the *meltwater corridor* term of Rampton (2000; esker scour channel of Craig, 1964; glaciofluvial corridor of St. Onge, 1984, and Utting et al., 2009) to a new glacial landform assemblage (architectural element), in which the corridor architecture consists of a number of different erosional and depositional landform elements/features; for example, s-forms, washed bedrock, eroded till, glaciofluvial lags, terraces, transverse forms, gravel bars, hummocks and eskers ([Fig. 7](#)).

4.5 Till surfaces

Surface continuity, relief, and boulder concentration are key attributes of till surfaces in the study area and are similar to those observed to the east of the study area (e.g., Sharpe et al., 2013; Rampton and Sharpe, 2014). Till veneer, less than 2 m thick, includes exposed bedrock and consists of loosely-compacted diamicton ([Fig. 32](#)) with high surface concentrations of cobbles and boulders ([Figs. 51, 52](#)). Till blanket, 2-5 m thick, occurs on

streamlined forms and has moderate surface boulder concentrations ([Fig. 28](#)), which may represent erosional lags.

The 0-25cm zone of reworked sediment on most diamicton surfaces ([Fig. 54](#)) is considered to be glaciofluvially-reworked till, or glaciofluvial deposits (e.g., Rampton, 2000), sometimes exhibiting evidence of periglacial activity. This interpretation is strengthened when the sample site is situated in erosional corridors or on terraces eroded into the flanks of drumlins ([Figs. 24-27; 32](#)).

4.6 Drumlins

Drumlins across the study area show evidence of erosion. Steep sculpted banks, terraces and scours are observed along the flanks and up-flow of stoss ends of numerous drumlin forms ([Figs. 22-27](#)). These features may be traced along a series of drumlins to define a continuous zone of erosional elements, channels, or the margins of erosional zones (e.g., Craig, 1964). Drumlins are also eroded where 1-3 km wide corridors abruptly truncate and cut across the continuity of drumlin forms ([Figs. 22, 31, 36](#)). Since corridors are floored with exposed, sculpted bedrock, thin sediment remnants ([Fig. 32](#)), and a surface concentration of cobbles and boulders ([Fig. 26](#)), abrupt corridor margins indicate that 10's of metres of drumlin sediment have been removed ([Fig. 36](#)) to produce these exposed rock-corridor floors. For example, where a corridor has truncated a 25 m drumlin to bedrock, 25 m of drumlin sediment has been eroded. Where erosion on a drumlin forms a terrace the remaining sediment has been modified to varying degrees by corridor-forming meltwater erosion.

Surfaces at the top of a drumlin often contain a concentration of cobbles and boulders, but to a lesser extent than upflow (stoss) and flanking settings. Terraces formed on the flanks of drumlins ([Figs. 23, 25](#)) also contain a concentration of cobbles and boulders, in places forming gravel sheets ([Fig. 30](#)). These observations are supported by sample pit observations, which indicate a concentration of rounded to sub-rounded gravelly sediment on the surface of drumlins, terraces, eroded banks and corridors compared to that from buried sediment sampled from sample pits ([Figs. 32, 51, 52](#)) (surface to pit stone concentration is $> \sim 2:1$). The concentration of coarse sediment in a number of terrain settings implies the removal of matrix sand and silt by a widespread erosive process, most likely due to glacial meltwater.

Scour zones often occur on the upflow ends of drumlins and contain the highest concentration and the largest clasts (mainly boulders) in this landscape ([Fig. 29](#)), indicating that erosive meltwater had a directional trend ([Figs. 35, 37](#)) that parallels drumlin orientation.

The presence of gravel bars ([Fig. 34](#)) and transverse ridges in some corridors ([Fig. 38](#)), including where drumlins have been eroded, indicates the transport and deposition of coarse sediment along the corridor floor most likely occurred when the erosional flow waned. Most corridors contain eskers and associated hummocks, implying that the

erosive flows were likely subglacial (e.g., Utting et al., 2009) or at least ice-walled over many 10s of kilometres of corridor length.

The occurrence of sand-cored drumlins, identified by prominent gullies cut into the drumlin flanks (Figs. 25, 33), indicates that the full drumlin form is erosional, and not just truncated by corridors and terraces. As observed in a drumlin flank (Fig. 33) and in a drumlin end-section, the outer form of individual drumlins clearly truncates the bedded sediments within a diamicton carapace and the horizontal sandy beds beneath it.

4.7 Eskers

The regular east-west-trending radial pattern of esker ridges (Fig. 39) represents a regional meltwater drainage that parallels the synoptic ice sheet flow direction inferred by Craig (1964) from streamlined landforms. The association of eskers with widespread erosional corridors indicates that erosive subglacial meltwater flow may have determined the extent and distribution of the esker network, assuming that the network elements formed synchronously over large areas (at least many tens of kilometers along the flow path). The esker network is quite regular, having 8–10 km spacing for several hundred kilometers (e.g., Sharpe et al., 2013). The variety of sharp to round-crested undulating, to flat-topped profiles (Figs. 40-42), single to multiple crestlines (Fig. 43), some with depressions interpreted as kettle holes connected by sand areas, aprons, hummocks and mounds, or by sediment-free bedrock zones, all indicate complex esker formation. Whether eskers formed in short segments (<25km) related to ice-marginal retreat, or whether they formed longer segments (>25km) will likely require detailed architectural element mapping to elucidate. However, overall corridor formation (length > 100 km in the immediately adjacent area to the west; Sharpe et al., 2013) may be an important precursor for esker location, size and length (extent).

4.8 Ice marginal landforms

End moraines were not observed in the study area (Fig. 39) or on the surficial compilation map of Aylsworth and Shilts (1989c; Fig. 3), and for ~100 km downflow (Kerr et al., 2013), or upflow of the study area. Eskers are often used to define ice-marginal positions (e.g., Lee et al, 1957; Craig, 1964; Aylsworth and Shilts, 1989a), particularly where an esker-ridge fan or delta relationship can be defined. The assemblage of sandy aprons, fans and hummocks does not often occur in a linear fashion normal to ice flow and thus does not clearly define ice marginal positions. In the southwest portion of the study area, the esker systems consist of an expanding array of low-relief flat-topped esker segments (Fig. 43); some show braided patterns, with a number of kettle depressions. From this study it is not clear if this sub-aerial character is related to formation as an open channel (loss of ice roof) esker, or as an ice-marginal feature. However, most esker segments occur within long (> many 10s of km), wide erosion zones (corridors) that frame the extensive esker networks of the area. This landform association implies that most esker segments are formed over the scale of at least many 10's of kilometers. The close spatial association of corridors and eskers raises the possibility that discontinuous eskers do not represent time-transgressive segments but rather depositional gaps associated with local topographic variability and/or flow variability within the esker conduit (cf. Brennand 1994). The implication is that corridors

may provide evidence of ‘process continuity’ that allows esker segments to be linked over longer distances. The absence of ice marginal deposits near eskers within a corridor is the strongest justification of this process continuum between eskers and corridors. This hypothesis requires further examination and field testing but provides a novel interpretive framework for the extensive esker network of the Keewatin.

4.9 Post glacial lakes and shorelines

The inferred glacial shorelines of Craig (1964) at ~380 m asl to ~350 m asl in the north-trending part of the Thelon Valley (Fig. 3) are at the same approximate elevation as observed concentric ridge lines, terraces and spit-like features observed on some drumlins (Fig. 47). These features and the presence of sub-rounded gravel clasts suggest they could be related to shoreline processes. However, the absence of clast-shingling or imbrication on these landscape elements, and the general lack of these features on readily reworked esker sediment, argues against widespread shoreline reworking. Shoreline features most likely occur as concentric flights or multi-stepped features that wrap around topographic highs, such as the prominent terraces just west of Thelon River (Fig. 3), but note to the extent shown on recent air photo-interpreted surficial maps (e.g., Dyke and Kerr, 2014).

Scour pit flow indicators and grading of gravel with flow direction are more compatible with glaciofluvial flows. The similarity of sand /gravel concentrations on concentric and non-concentric terraces could indicate ephemeral shoreline reworking of glaciofluvial terraces, particularly on the prominent terraces just west of Thelon River (Fig. 3). However, the lack of fine-grained lake deposits and small sandy deltas, as inferred by Craig, 1964, also minimizes the role of glacial lakes and associated shoreline processes. We further note that organic deposits were not observed in the study area, in contrast to recently-published, airphoto-interpreted surficial maps that were not verified by on-ground observations (Stea and Kerr, 2014).

4.10 Periglacial/ permafrost features

Freeze-thaw processes in periglacial/ permafrost terrain modify and alter the landscape at various scales due to the presence of extensive discontinuous permafrost. Thus cryoturbation can mix sediment in the active layer, for example mixing till and glaciofluvial sand, potentially to a depth up to 50 cm (Sharpe and Rampton, 2014).

4.11 Existing landform models

During Operation Keewatin (~1952-55; Wright, 1957, 1967) fundamental landscape forming concepts, which explained the directional landforms and deglaciation of the LIS, were formulated by Lord, 1953; Lee, in Lord, 1953; and Fyles, in Wright, 1955. This synoptic work set out the founding conceptual landform models for the region that are often endorsed (e.g., Dyke 2004). These studies infer that ice moulded/deposited sediment into drumlin ridges and furrows parallel to striated rock surfaces, thus producing an arcuate SW to NW flow pattern that also deposited a mantle of till with boulder fields. Eskers, terraces and abandoned stream channels form an integrated drainage system that fans westward in a similar SW to NW array. Most glacial flow features, drumlins and related directional forms, inferred minor moraines, and eskers were considered to have formed by numerous, successive ice movements near the glacier

margin during ice marginal retreat (Lee, 1959; Craig, 1964). This model also considered that, as deglaciation progressed eastward, widespread pro-glacial lakes formed where glacial ice dammed major eastward-flowing streams (Fyles in Wright, 1955; Craig, 1964).

4.12 Landform models and sediment dispersal concepts

Based on observations from this study, we suggest that several concepts from long-held surficial landform models should be re-assessed: *i*) drumlins in the region are till depositional landforms; *ii*) drumlins formed time-transgressively at former ice margins; and as a corollary, do not represent the paths of long continuous glacial flow; *iii*) eskers formed time-transgressively at former ice margins; and the corollary, do not represent the paths of long continuous drainage networks; and, *iv*) all terraces in the region are shoreline features of former pro-glacial lakes, which were used to define a pattern of sequential west to east deglaciation. If these landforms models are to be revised as our new field data suggest, there are likely to be highly important implications on the erosion, transport and dispersal of sediment for mineral exploration purposes. We review these implications, till and glaciofluvial sediment as sample media, and terrain element sampling.

4.12.1 Till as a prime sample media

Erosion, transport and deposition of glacial sediments are complex (Alley, 1997), yet there has been little new work on how sediment is eroded, transported and deposited as till (Hooke et al., 2013). Nevertheless, most ‘drift’ exploration sampling uses till as the unique media to trace dispersal patterns (e.g., Klassen, 1995; McClenaghan et al., 2007; McMartin and Paulen, 2009). It is well established, for example, that mud-boil samples of till are the preferred geochemical sampling medium in glaciated terrain (e.g. McClenaghan et al., 1997, 2002) with subsequent geochemistry determined by aqua regia partial dissolution determined on the clay, or the clay-silt, fraction of till.

In the Thelon study area, till surfaces appear to be erosional. Most till veneer, which is common in glaciofluvial corridors and on bedrock expanses of the study area, is interpreted to be the result of widespread erosion /reworking as indicated by the common occurrence of gravel lags. The thin remnant sediment most likely represents particles derived from local bedrock due to local transport (e.g., Klassen, 1995). In contrast, areas with thicker till, or on the surface of thick drumlins, are less likely to have predominant sediment from local bedrock sources. Thus, it is possible that adjacent till samples, one from an erosional corridor and one from a thick drumlin, possess a different transport path and provenance, an issue first identified by Rampton (2000) in an erosional terrain (the Lac de Gras area) ~ 500 km downflow of the current study area. Where thick, sorted glaciofluvial sediments occur in drumlins with thin diamicton caps ([Fig. 33](#)), further illustrates a dilemma for the wholesale ‘till-as-a-sampling-media’ question.

4.12.2 Glaciofluvial sediment as a sample media

Some key exploration success has involved esker sampling (Kjarsgaard and Levinson, 2002; Cummings et al., 2011a, b), although glaciofluvial sediment has typically been used far less than till as a prospecting media. Heavy mineral analysis however, has not been regularly carried out on both till and glaciofluvial sediment (e.g., McClenaghan and Kjarsgaard, 2007). However, sedimentary deposits may record multiple transport processes (i.e., ice and water) and complex transport pathways (Rampton, 2000; Rampton and Sharpe, 2014); hence, a systematic till-esker sample design was carried out in this study that duplicated the till-esker sample design successfully carried in the East Arm area to the west (Kjarsgaard et al., 2013a).

4.12.3 Drumlins and flow direction indicators for mineral dispersal

If drumlins are ice-related depositional features and composed of till (e.g., Menzies, 1979; Boulton, 1987), as most exploration studies assume, then the orientation of drumlins is expected to correspond with dispersal patterns from till samples (e.g., McMartin and Paulen, 2009). This study, however, documents that drumlins in this study area are erosional features; scoured in the form of sculpted banks and terraces where internal strata are truncated by the eroded drumlins; in places up to 10 to 20 m or more of sediment was removed, especially in corridors. In addition, most drumlin surface sediment has been reworked in the top 0-25 cm and gravelly erosional lags are commonly observed. Hence, we suggest that dispersal patterns observed in till may or may not align with drumlin orientation, i.e. ice-flow and glaciofluvial flow directions are not necessarily concordant (e.g. Liverman and Vatcher, 1992). Despite these potential complications, sediment dispersal (based on till geochemistry and heavy mineral studies) from the adjacent East Arm area, also occur in a simple pattern (expanding-arcuate) that is aligned with erosional drumlins (Kjarsgaard et al., 2013a,b; Sharpe et al., 2013).

4.12.4 Drumlins formed time-transgressively at former ice margins?

The concept, that drumlins were formed as till depositional intervals (~10-25 kilometres wide perpendicular to the ice-margin) at successive former ice margins across the area, is firmly entrenched in the literature (Lord, 1953; Craig, 1964; Dyke, 2004). If this concept is true then transport lengths on the scale of 10's of kilometres would be expected within the study areas extensive (>1000 sq km) drumlin fields. However, sediment transport data from East Arm (e.g., Kjarsgaard et al., 2013; Sharpe et al., 2013) and this study (Kjarsgaard et al., 2013b; Knight et al., 2013) record transport lengths of up to ~200 km for Thelon basin sandstone clasts (with the assumption of transport by the latest flow). Variable mineral transport lengths do occur in till (~1 to > 100 km; mineral species dependant; Kjarsgaard et al., 2013b); this suggests that transport at 10's km scale, as implied by the flow model of Dyke (2004), is problematic.

Observations in the Thelon area and elsewhere indicate that drumlins occur in well-defined fields (Alysworth and Shilts, 1989) with well-delineated flow lines, tracts (Shaw et al., 2010), or flowsets (e.g. Stokes et al., 2006) on the scale of 100's km downflow. Hence, drumlins could represent the paths of long glacial flow paths (potentially

hundreds of kilometres in length), based on the continuity of directional features and streamlined forms, and, the implied flow integrity within a drumlin field.

4.12.5. Eskers formed time-transgressively at former ice margins?

The concept that eskers formed time-transgressively at former ice margins is a common theory (Lee, 1959; Dyke, 2004). Alternately, some consider that eskers represent the paths of long continuous meltwater systems, up to 300-400 km long (Craig, 1964), with unbroken segments (scoured areas of sand and gravel or bedrock stripped free of till) up to 75 km in length (Aylsworth and Shilts, 1989a). Craig (1964) nonetheless, interpreted esker as a series of segments formed at ice margins, whether ice-marginal landforms were observed, or not. The evidence for, or against, the formation of eskers as short segments at former ice margins, or as longer sediment transport systems, involves recognizing and mapping ice marginal features. At present, empirical evidence (e.g., Cummings et al., 2011; Sharpe et al; 2013), shows that esker sourced sediment is derived predominantly from adjacent eroded till with comparable transport distances; this evidence does not clarify whether sediment transport was based on the short or long esker model as dilution may have affected longer esker transport. It appears however, that esker transport is somewhat longer than transport in till. Kjarsgaard et al., (2013b) plotted individual indicator mineral types to determine transport distances based on known or inferred source region(s) for the indicator minerals, observed in both till and esker sediment. In the nearby East Arm study area, chalcopyrite, arsenopyrite, and loellingite grain-transport distances are suggested to be <1 to 3 km in till, and <1 to 20 km in eskers sediments. Olivine, chromite (Cr-spinel), and low Cr-diopside grains have been transported <1 to 70-90 km in till and <1 to 100-130 km in eskers sediments. Transport distances indicate that olivine < Cr-spinel < Cr-diopside. These till and esker transport distances are greater still when the contiguous data of Knight et al. (2013), East Arm and this Thelon study area are considered together.

4.12.6 Terraces are shoreline features of former pro-glacial lakes.

Previous studies have not recognized the possibility of glaciofluvial terrace erosion on drumlin flanks. These bench-like features were considered to be former glaciolacustrine shorelines (e.g., Craig, 1964; Dyke, and Kerr, 2014) and/ or glaciofluvial terraces with gravel concentrations, sediment lags or bedforms that armour underlying till ([Figs. 25, 27](#)). Locally, stone layers, which are in alignment with other paleoflow features ([Figs. 30, 34, 35, 37](#)), form coarse up-flow to finer down flow sediment arrays, are likely glaciofluvial indicators.

4.12.7 Terrain element sampling

The variety of glacial terrain elements in the Thelon study area is interpreted to have resulted from variable erosional, depositional, or combined processes. Understanding these processes is fundamental for mineral exploration purposes. Hence, it is important to describe the sample site and setting as accurately as possible with respect to terrain characteristics. Ideally, sampled sediment from specific glacial terrain elements, as described here, should be compared with samples from similar settings. It is possible that till transport and deposition (Hooke et al., 2013) may be dissimilar at adjacent sites

sampled in different terrain elements; the reasoning likely also applies to glaciofluvial sediment (Rampton et al., 2000) as different processes can produce different transport lengths.

5.0 Discussion

Newly mapped glacial features and associated sediment observations are in conflict with the long-standing conceptual landform models that have been used to guide drift exploration methods (e.g. McMartin and Paulen, 2009). In the Thelon study area, drumlins are interpreted as modified erosional landforms that may not be linked to the till transport event. Eroded drumlins display till thickness variation that may affect interpretation of dispersal patterns. Drumlins may be in alignment with the sediment transport direction based on a number of recorded dispersal patterns (Kjarsgaard et al., 2013b) in the region, or, it may be discordant.

Eskers have been considered to form close to ice margins and to be linked to inferred ice marginal features and positions (Lee, 1959; Craig, 1964). While ice-marginal formation is still a topic of debate (see Cummings et al., 2012), esker sediment is commonly sourced from nearby till; however, esker sediment shows slightly longer dispersal lengths than till (Cummings, 2012). This finding also applies to esker-till sampling in the East Arm study area to the west (Sharpe et al., 2013). It is possible that at the local to property scale, systematic mapping of esker landform architectural elements (e.g., corridors, ridges, fans, hummocks) and their sediments may be an aid to assessing mineral exploration dispersal patterns (e.g., Rampton, 2000).

The recognition of erosional corridors with inset esker ridges is significant to landscape origin and to the application of sediment dispersal studies in glaciated terrain. These 1-5 km wide erosional corridors may extend for ~50-100 km or more into downflow areas to the west of this study (e.g., Sharpe et al., 2013). The presence of corridors supports the former presence of meltwater drainage systems and potential transport pathways with long length-scales. Corridors have also been mapped in other glaciated terrain and interpreted to represent lengthy, evolved drainage networks (e.g., Burke et al., 2011; 2012).

Within the field area there are many observations that relate to widespread glaciofluvial erosion, e.g., s-forms, scours, sculpted banks, terraces, till remnants, gravel lags, gravel forms and erosional corridors. These observations appear to be in accord with widespread meltwater drainage. Energetic glaciofluvial drainage events may produce long, narrow indicator dispersal patterns (ribbon-shaped) such as those found in glaciofluvial sediment in Slave province (Rampton and Sharpe, 2014).

Similar to lakeshore reworking of esker sample sites providing an enriched heavy mineral sample medium for the discovery of kimberlite in the Lac de Gras area (Krajick, 2001), reworking of landforms and sediment by glacial lake or glacial fluvial processes may provide a 'placer' effect, in lag gravel settings (Cummings et al., 2012).

As the study area resides within the zone of extensive, discontinuous permafrost, periglacial activity may have reworked transported indicators. For example, sand-sized indicator mineral grains that were glaciofluvially-eroded, transported and then deposited on top of till have undergone subsequent cryoturbation that mixed indicator minerals from the till and overlying glaciofluvial sediment.

All till sites in the current study area have been eroded to a varying degree; hence, it is feasible that samples from the current land surface have different transport histories. For example, till in erosional corridors occurs as thin remnants on bedrock. Such till likely records local bedrock whereas samples from sites with thicker sediment /till likely travelled further. In addition, glaciofluvial sediment occurs in a number of terrain settings; eskers, transverse ridges, terraces and glaciofluvial lags on a number of different terrain surfaces. To help decipher sediment dispersal patterns, it is important to note the specific details of the terrain elements being sampled, if and where it is not feasible to carry out a comprehensive sampling scheme of specific terrain elements.

Mineralogical or geochemical masking may be important to mineral exploration. It is our recognition that, till and eskers sediments are not only sandy, but the sand is quartz-rich, being derived from quartz sandstone source rocks in the Thelon Basin to the east (Kjarsgaard et al., 2013a, 2014). From this two basic principles of the application of surficial sediment sampling to mineral exploration via heavy minerals or geochemistry are worth noting: 1) the target 'ore' source material will be diluted when incorporated into 'background' transported sediment; and, 2) the diluting sediment can also (and typically does) mask the signature of the source target. In the study area, there is dilution by quartz-rich sand in all types of surficial sediment and terrain elements. However, the quartz-rich sand dilutant does not provide a mineralogical mask, nor a geochemical mask. This suggests that target anomalies could in fact be easier, and not more difficult to detect in such settings (Kjarsgaard et al., 2014), despite terrain element and transport complexity.

6.0 Conclusions

Erosion, transport and deposition of glacial sediment involve complex processes (Alley, 1997) that may be imperfectly recognized by exploration geologists. Thus, sediment sampling and analysis should take into account specific glacial terrain elements of mapped glacial landscapes. In this study area, in the East Arm (Sharpe et al., 2013) and in the Slave (Rampton and Sharpe, 2014) to the west, there is evidence for erosion and deposition by glacial-ice processes and by glacial-meltwater processes. Thus, to accurately assess the direction and distance of sediment transport requires consideration of multiple primary processes, and secondary (cryogenic) processes recorded in landforms (e.g. eskers, drumlinized till) and sediment attributes (e.g. striations, rounding).

We suggest that targeted mineral exploration based on terrain analysis and sediment sampling of till and glaciofluvial sediment is of utmost importance in a successful mineral exploration program. This sampling plan should accommodate an assessment of the degree and effects of meltwater /ice erosion and/or deposition and integrates the findings into regional mineral-exploration strategy (e.g., Kjarsgaard et al., 2013a; Rampton and Sharpe, 2014). For example, sampling of specific sedimentary features, such as glaciofluvial forms, lags, and corridors to assess the influence of different processes of sediment transport (e.g. ice, meltwater) as well as secondary processes such as cryoturbation, could improve exploration success.

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9.0 Figure Captions

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Figure 5. Sample map with locations of till and esker samples for 2012.

Figure 6. Glacial erosion features (e.g., striae), and s-form, with generalized flow direction noted in the Thelon study area.

Figure 7. Conceptual model of the predominant terrain elements in the study area; highlighted are s-forms (W), eroded bedrock (RM), sculpted bank (SB) eroded till (Tv) (till veneer), glaciofluvial terrace, glaciofluvial lag, hummock (H), fan, transverse ridge (TR), gravel bars, terraces, corridor and esker (E). Drawing by John Glew, Queens University.

Figure 8. Bedrock platform (bp) as uplands with intervening channels (ch); note gravelly sediment (s) in the lee of rock protrusions; flow was left to right (west) parallel to furrows (f).

Figure 9. Bedrock channel (BC), incised into bedrock expanse with thin scattered sediment cover; channel walls are ~ 15 m high.

Figure 10. Bedrock platform (bp) with sediment (S) concentration on the down flow side of a scoured rock upland; note largest boulders are on the rock surface, with smaller boulders on the near sediment and finer gravel further away and downflow; erosional furrows (f) define streamlining of the rock surface; flow direction was away from viewer.

Figure 11. Furrows (f) with faint striations (s) or small grooves next to arrow; note that the furrows define elongate rock ridges (best defined far upper left); furrows may be crescentic.

Figure 12. Faint striae (s) on polished rock surface; striae are rare in the area; arrow is ~2 cm long.

Figure 13. Sculpted rock forms, whalebacks (wb), with pointed end up flow (left), and blunt, smooth end down flow (right); whalebacks (wb) are defined by erosional furrows (f) on either side of an upstanding ridge; note the few boulders scattered on the rock surface.

Figure 14. *Roche moutonnées* display sharp down flow edges (fe), and often have grooves (g) on rock surface. Note the boulder cover in background with a mix of angular to rounded boulders.

Figure 15. Whalebacks (wb) with prominent straight furrows (f) and crescentic furrow (cs) which define small rock ridges or rock drumlins; such crescentic stoss-side and lateral furrows are considered to be s-forms (Kor et al., 1991); note the sparse boulders in background; flow is away from viewer along the trend of hammer handle (~20 cm long).

Figure 16. Boulder concentration (many rounded/ sub-rounded/ some sub-angular) on whalebacks (wb).

Figure 17. Rock crag (c) and sediment tail (t); exposed bedrock around crag and tail, and till veneer in foreground; flow right to left.

Figure 18. Large channel consists of over-deepenings (series of depressions (o) with lakes) along its length; channel cuts through bedrock expanse.

Figure 19. Scoured bedrock with comma-shaped s-form (cf); note boulder-covered surface in background; flow away from viewer.

Figure 20. Hairpin scour (HS) on smooth eroded, whaleback rock surface; flow was from right to left.

Figure 21. Drumlin field where forms occur as individual symmetric forms, spindles (ds), asymmetric (A), or as groups of (en echelon) forms (g); flow is from top left to lower right (west); note different vegetation on north (brown) and south (tan) slopes; tan colour highlights terraces (t) on drumlin flanks.

Figure 22. Drumlins (d) in association with crescentic lakes (cl) which truncate drumlins (dt), where the lake then continues as a flow parallel depression (fp); drumlins show prominent vegetation bands (dark and light coloured zones) which highlight benches or terraces (t) on drumlin flanks; a sculpted bank (SB) occurs on the outside arm of the crescentic lake where it truncates a drumlin upland (d, lower part of image).

Figure 23. Drumlin shield downflow of crescentic lakes (CL), or towards viewer, with three prominent drumlins (d) defined by furrows (f) that extend downflow from crescentic lakes; benches or terraces (t) are prominent on drumlins flanks adjacent to furrows.

Figure 24. Drumlin (d) erosional scarp or sculpted slope or bank (SB) and terraces (t) indicate drumlin erosion.

Figure 25. Asymmetric drumlin upland (A) with terraces (t) on the upflow side extending to drumlins flanks; note gullies (g) eroded into sandy eroded terrace scarps; transverse ridges (TR) occur in lee of asymmetric drumlin upland; gravel concentration (grey tone) occurs on stoss, lateral and lee surfaces. Note drumline truncation (dt).

Figure 26. Drumlin terrace is indicated by a sculpted bank (SB) and concentration of rounded boulders in foreground; notebook (nb), 11 x17 cm for scale.

Figure 27. Stoss-side troughs form a series of arcuate, crescentic lakes (CL) that extend across multiple drumlins (d) flanked by furrows (f), terraces (t) and sculpted banks (SB); flow was toward the viewer.

Figure 28. Symmetric drumlin with scattered boulder cover; sculpted bank (SB) defines lateral drumlin depression; note sandy terrace on the downflow end of the drumlin; view is upflow to the west.

Figure 29. Stoss end of drumlin with upflow depression (lakes) in the background; note concentration of large, sub-rounded boulders; diamicton was sampled below the gravelly surface sediment.

Figure 30. Terrace gravel is predominantly rounded boulders with largest sub-angular clasts on drumlin flank; note boulder blanket over a 5-10 m elevation range.

Figure 31. Low relief drumlins (5-15m) form a truncated remnant upland (4 labeled drumlins, d) in wide corridor (dashed) adjacent to sandy esker (E) with narrow and broad segments (sandy); note eroded bedrock (R) next to esker; view and flow away from viewer to west.

Figure 32. Inter-drumlin sample site has thin sandy diamicton and surface gravel concentration; a typical sample pit in a corridor setting.

Figure 33. Example of a drumlin (d) formed by erosional processes displaying over 30 m of thick, horizontally-bedded sand with multi-level terraces (t) underlying thin diamicton on banks of the Mary Francis River; paleoflow was left to right.

Figure 34. Terrace gravel with predominant rounded to sub-rounded boulders; note sorting of coarser clasts to the higher (near side) of the terrace; terrace is set between two scoured rock uplands with scattered sub-rounded boulders; note person in white outfit for scale.

Figure 35. Large boulder with vegetated depression and no gravel in depression around the boulder; inferred to be a scour pit (dashed line); flow towards the viewer; notebook (11 x17 cm) for scale.

Figure 36. Channel (ch) eroded several drumlins (d), defined by a sculpted bank (SB) and a terrace (t) along a drumlin flank; note small sandy esker ridge to left of channel.

Figure 37. Gravel bar (gb) with larger clasts to right and smaller clasts to left (downflow).

Figure 38. Transverse ridges (TR), ~2-7 m high, ~10-15m wide and ~100-150 m long, often run perpendicular to the corridor long axis and adjacent to esker (E, light sandy ridges).

Figure 39. LANDSAT image of esker-drumlin pattern near the Thelon river (east central) shows eskers (white) trending east-west, ~8-12 km apart; width of scene is ~100 km; note white areas with sandy sediment have gaps (lakes) where erosion was prominent. Red symbols are drumlins.

Figure 40. Single crested, flat-topped esker ('railway embankment' type) with sandy aprons or fan (F) adjacent to esker ridge (E); note exposed bedrock (R) with scattered boulders adjacent to esker.

Figure 41. Complex array of esker types and morphologies, sharp-crested (e) transitional from flat-topped (f); note esker ridges and mounds apart from the main esker ridges; sand and gravel terraces (t) occur with eskers and below a sculpted bank (SB) on a drumlin, a possible corridor margin; note lateral sediment aprons (A) and hummocky surfaces (h).

Figure 42. Single-crested esker ridges consisting of undulating mounds; note gravel occurs along the sharp esker crestline.

Figure 43. Single-crested ridge (s) leading to multiple bifurcations and re-attachments in sandy rounded /flat-topped esker ridges (b); note sandy hummocks (h) apart from main ridges.

Figure 44. Esker ridge (E) and fan (F) complex, set within a poorly-defined corridor (C, dashed line at margin); not sculpted bank (SB) on drumlin within corridor.

Figure 45. Single-crested (e) and flat-topped esker with gravel terrace (gt) adjacent to esker ridges.

Figure 46. Esker complex with ridges (r) and hummocks (h) in a wide zone; note erosional banks on drumlin flanks in background (dashed line).

Figure 47. Multiple, concentric ridge lines, or terraces occur on some drumlins, in places with spit-like extremities as in the truncated sandy terrain near Thelon River.

Figure 48. Sub-rounded gravel clasts occur in organized forms or ridges on terrace surfaces.

Figure 49. Large, 30-50 m diameter polygons (p) on drumlin uplands; polygons are smaller and poorly formed on better-vegetated north facing slopes.

Figure 50. Solifluction (S) modification of the slopes of a drumlin with terraced flanks.

Figure 51. Diamicton sample site contains angular to sub-angular clasts in greater abundance on the surface compare to subsurface (see screen fraction from 70 cm pit); note mud-boils in sediment patches within brown vegetation.

Figure 52. Sample site with more stones on the surface (~5-10%) than are present within sampled diamicton pit <3%.

Figure 53. Striated volcanic and sandstone clasts weathered out of sandy diamicton atop river bluff, Mary Francis River (see figure 7m).

Figure 54. Sample pit shows a ~15cm thick reworked, sub-rounded gravel layer over ~25 cm of stone-poor, sandy, buff-coloured diamicton.

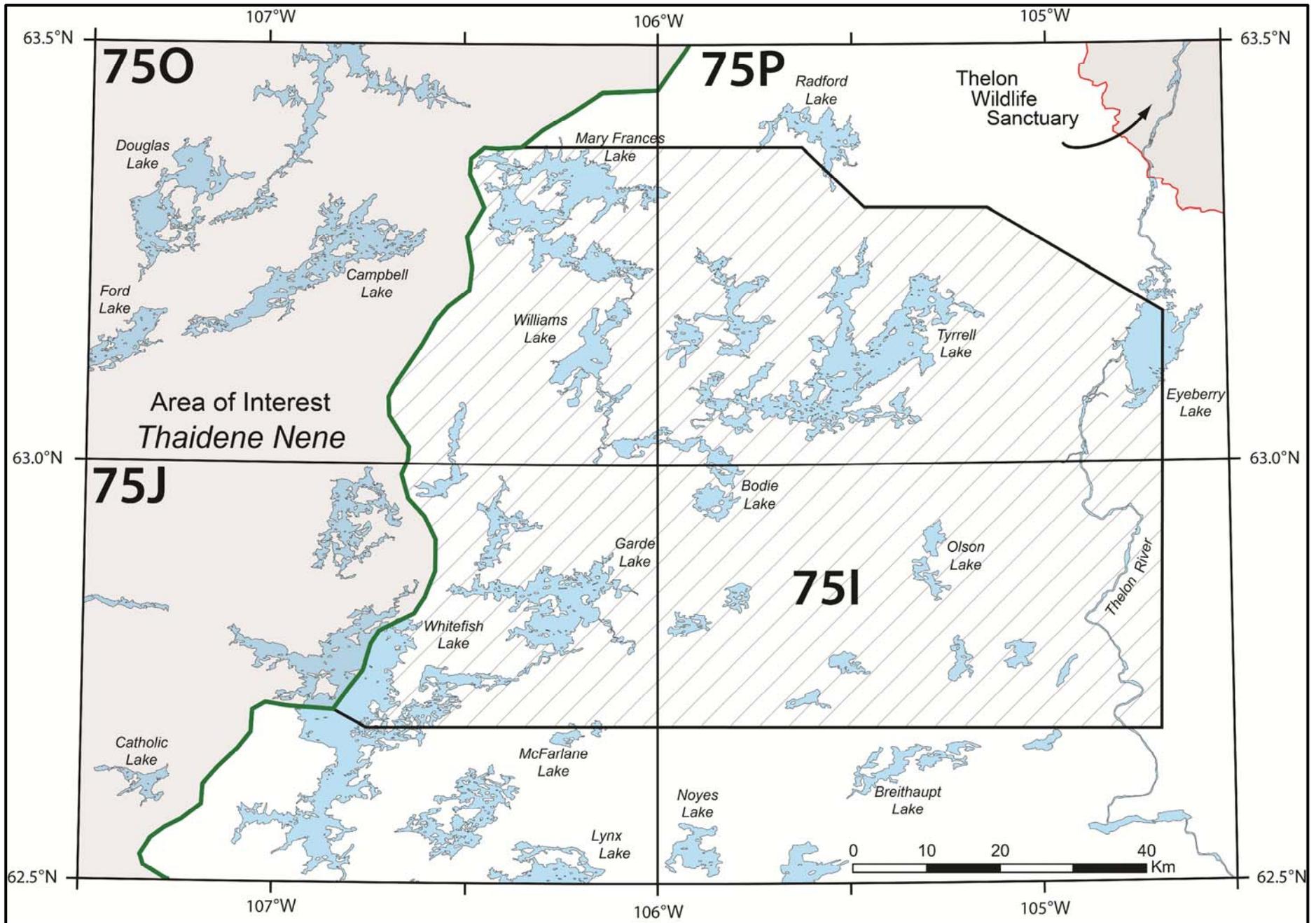


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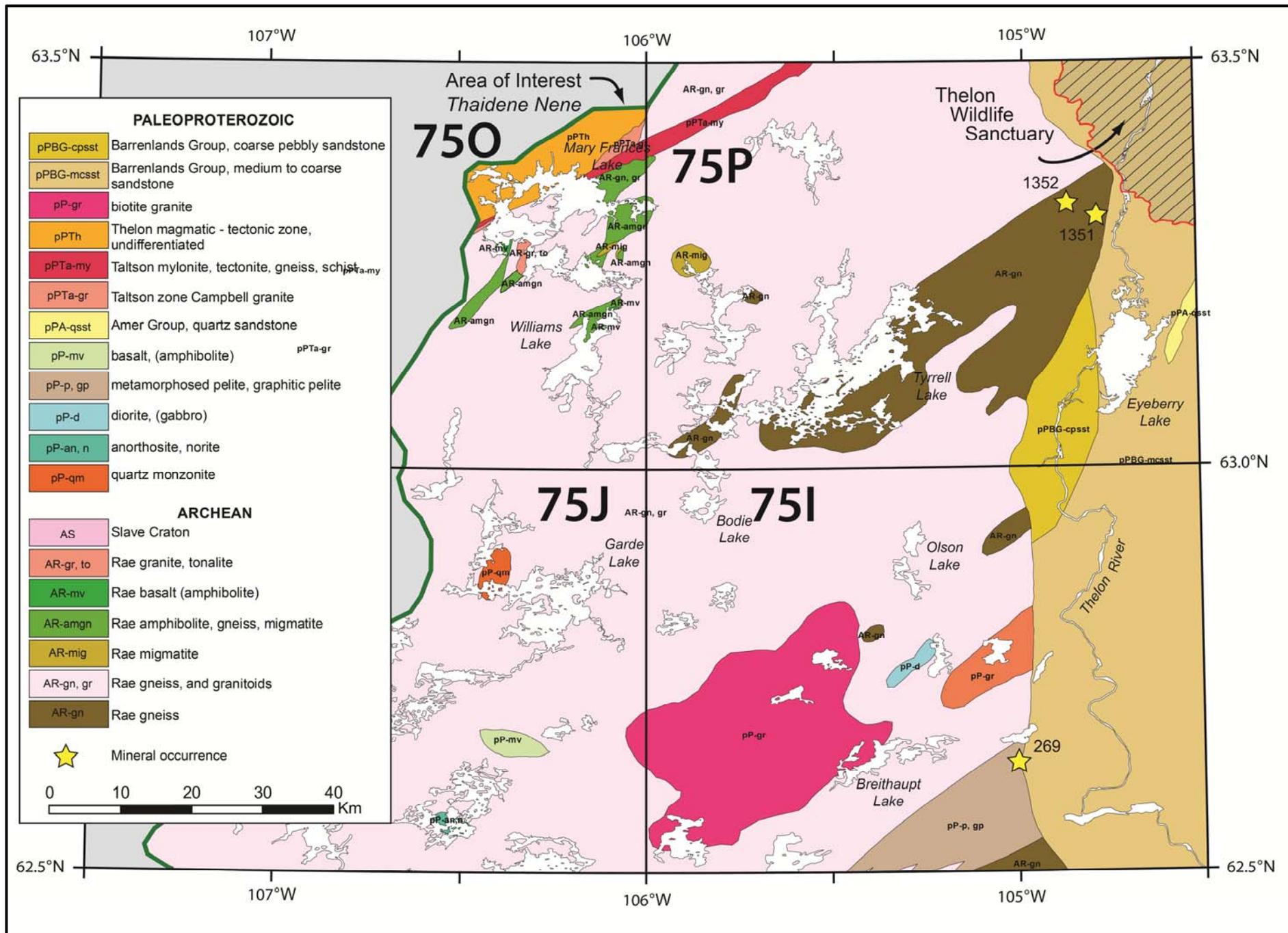


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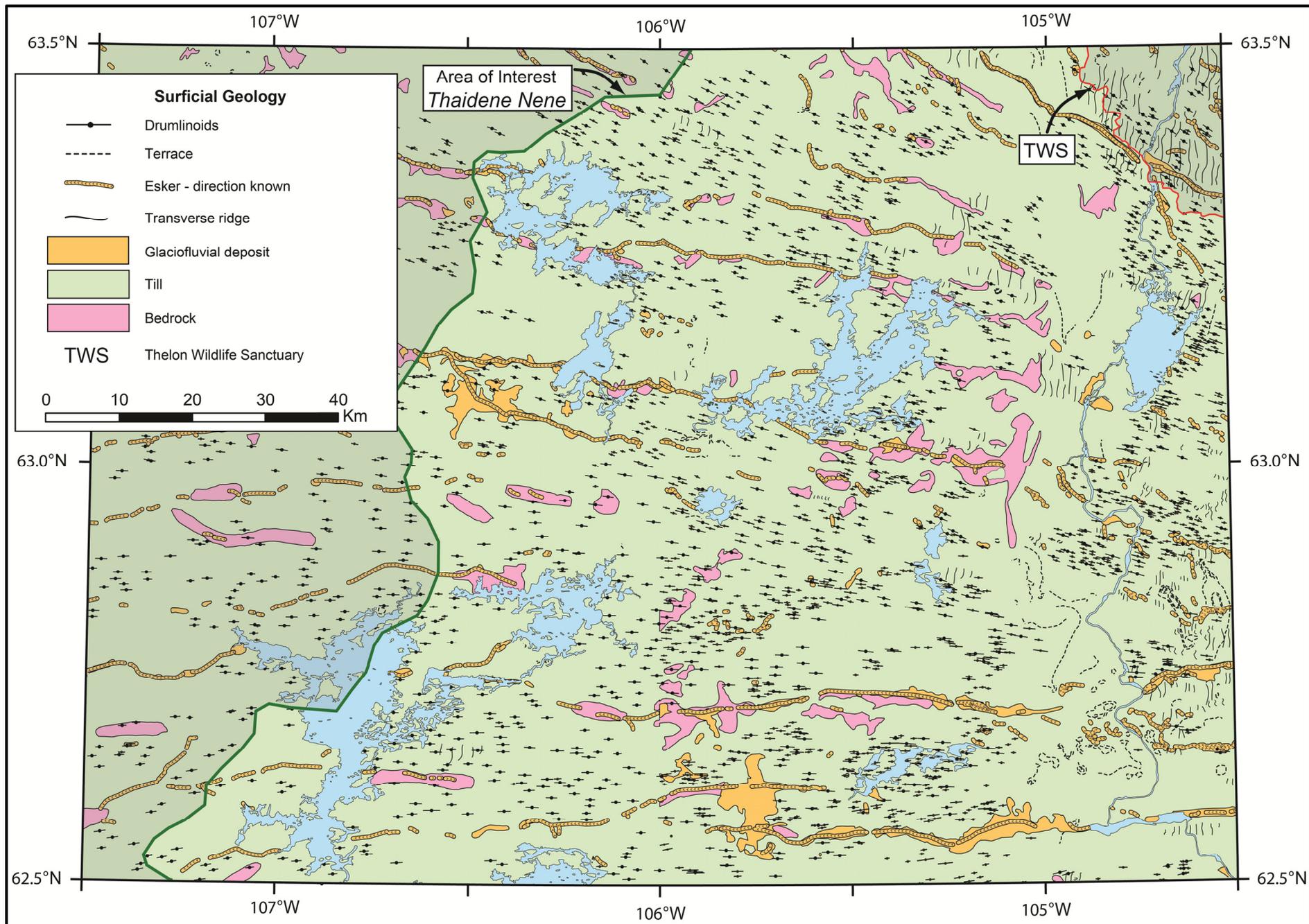


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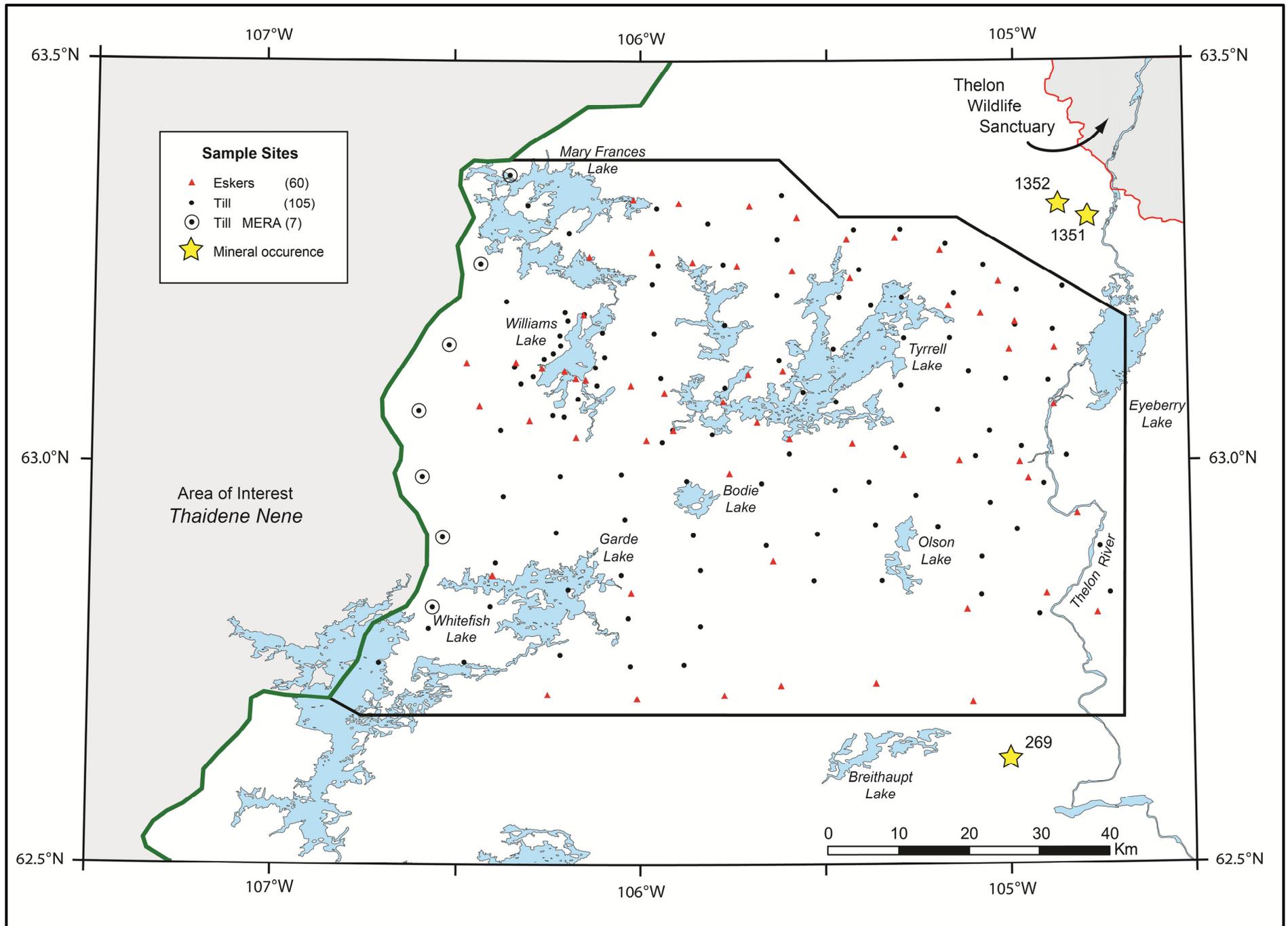


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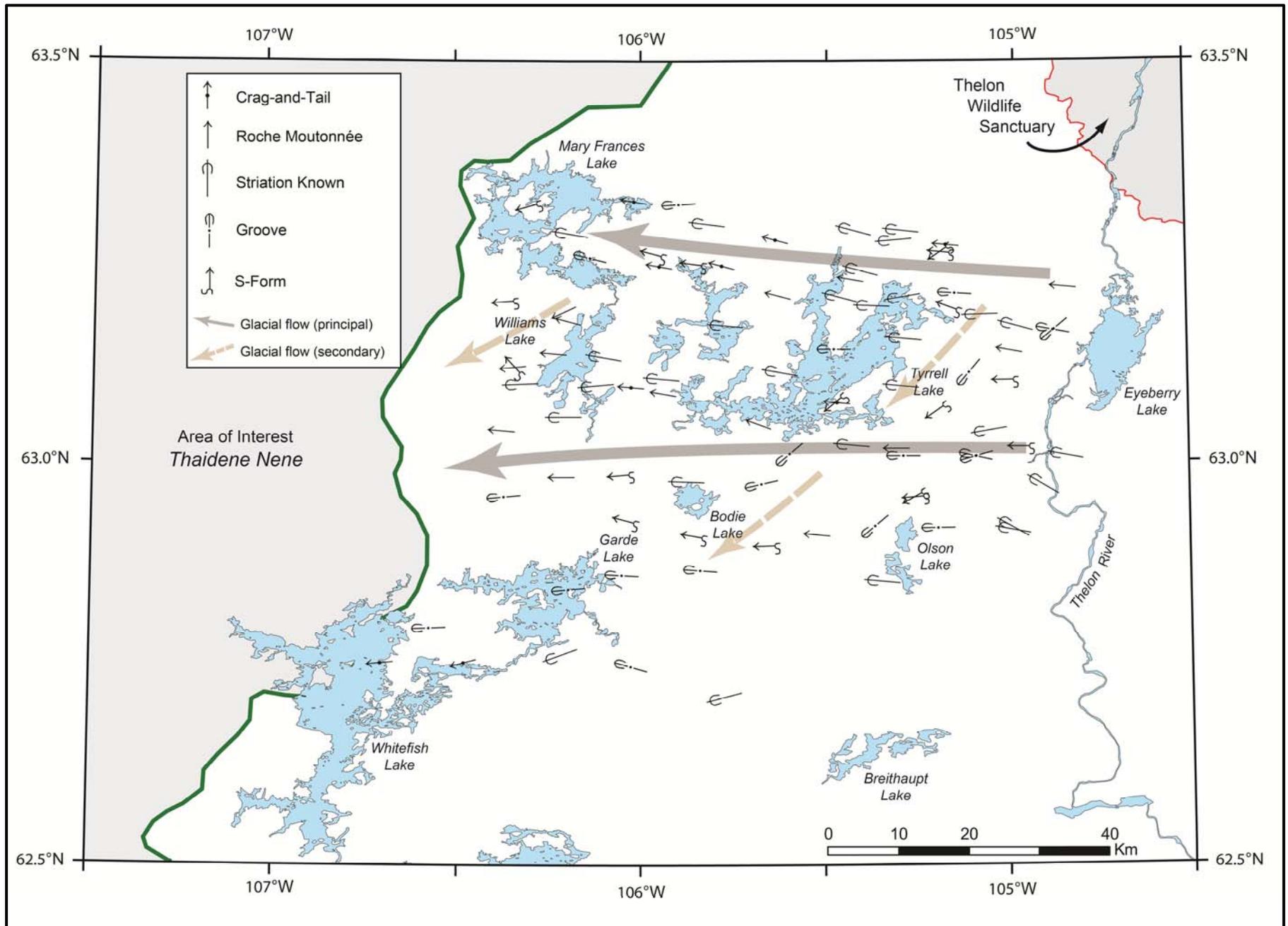


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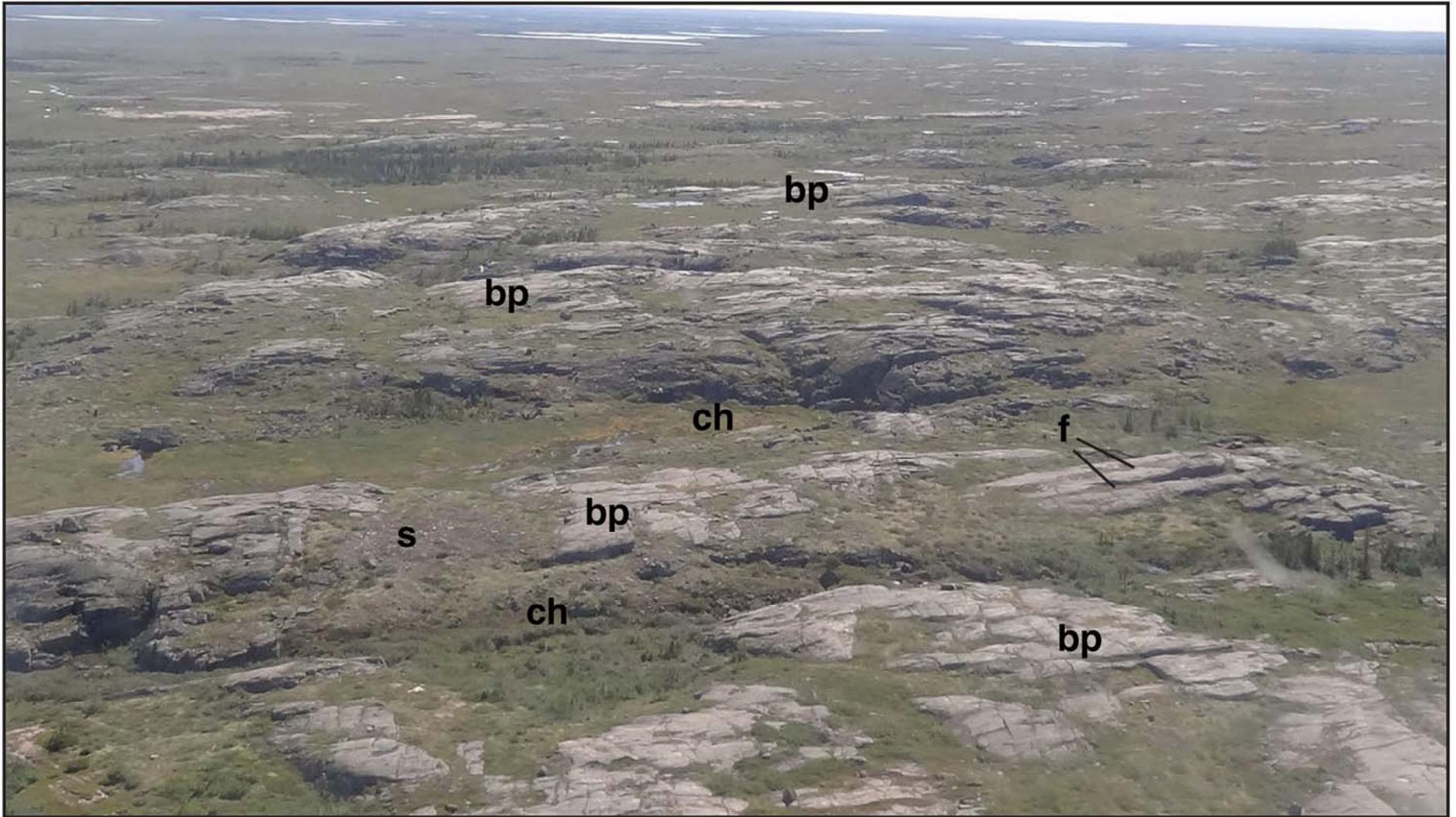


Figure 8. Bedrock platform (bp) as uplands with intervening channels (ch); note gravelly sediment (s) in the lee of rock protrusions; flow was left to right (west) parallel to furrows (f).



Figure 9. Bedrock channel (BC), incised into bedrock expanse with thin scattered sediment cover; channel walls are ~ 15 m high.



Figure 10. Bedrock platform (bp) with sediment (S) concentration on the down flow side of a scoured rock upland; note largest boulders are on the rock surface, with smaller boulders on the near sediment and finer gravel further away and downflow; erosional furrows (f) define streamlining of the rock surface; flow direction was away from viewer.



Figure 11. Furrows (f) with faint striations (s) or small grooves next to arrow; note that the furrows define elongate rock ridges (best defined far upper left); furrows may be crescentic.



Figure 12. Faint striae (s) on polished rock surface; striae are rare in the area; arrow is ~2 cm long.



Figure 13. Sculpted rock forms, whalebacks (wb), with pointed end up flow (left), and blunt, smooth end down flow (right); whalebacks (wb) are defined by erosional furrows (f) on either side of an upstanding ridge; note the few boulders scattered on the rock surface.



Figure 14. *Roche moutonnées* display sharp down flow edges (fe), and often have grooves (g) on rock surface. Note the boulder cover in background with a mix of angular to rounded boulders.



Figure 15. Whalebacks (wb) with prominent straight furrows (f) and crescentic furrow (cs) which define small rock ridges or rock drumlins; such crescentic stoss-side and lateral furrows are considered to be s-forms (Kor et al., 1991); note the sparse boulders in background; flow is away from viewer along the trend of hammer handle (~20 cm long).



Figure 16. Boulder concentration (many rounded/ sub-rounded/ some sub-angular) on whalebacks (wb).



Figure 17. Rock crag (c) and sediment tail (t); exposed bedrock around crag and tail, and till veneer in foreground; flow right to left.



Figure 18. Large channel consists of over-deepenings (series of depressions (o) with lakes) along its length; channel cuts through bedrock expanse.



Figure 19. Scoured bedrock with comma-shaped s-form (cf); note boulder-covered surface in background; flow away from viewer.



Figure 20. Hairpin scour (HS) on smooth eroded, whaleback rock surface; flow was from right to left.



Figure 21. Drumlin field where forms occur as individual symmetric forms, spindles (ds), asymmetric (A), or as groups of (en echelon) forms (g); flow is from top left to lower right (west); note different vegetation on north (brown) and south (tan) slopes; tan colour highlights terraces (t) on drumlin flanks.

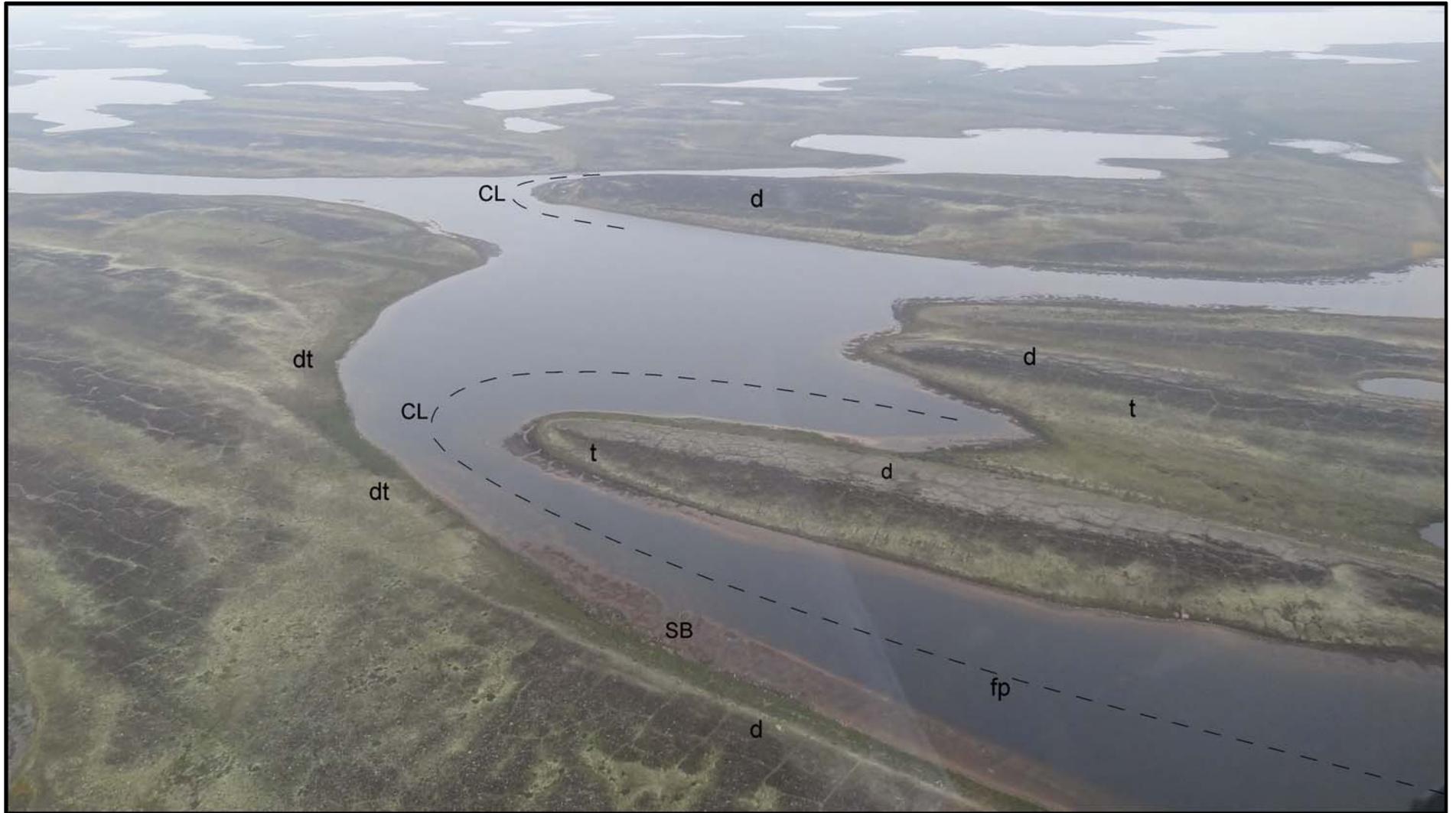


Figure 22. Drumlins (d) in association with crescentic lakes (cl) which truncate drumlins (dt), where the lake then continues as a flow parallel depression (fp); drumlins show prominent vegetation bands (dark and light coloured zones) which highlight benches or terraces (t) on drumlin flanks; a sculpted bank (SB) occurs on the outside arm of the crescentic lake where it truncates a drumlin upland (d, lower part of image).



Figure 23. Drumlin shield downflow of crescentic lakes (CL), or towards viewer, with three prominent drumlins (d) defined by furrows (f) that extend downflow from crescentic lakes; benches or terraces (t) are prominent on drumlins flanks adjacent to furrows.



Figure 24. Drumlin (d) erosional scarp or sculpted slope or bank (SB) and terraces (t) indicate drumlin erosion.



Figure 25. Asymmetric drumlin upland (A) with terraces (t) on the upflow side extending to drumlins flanks; note gullies (g) eroded into sandy eroded terrace scarps; transverse ridges (TR) occur in lee of asymmetric drumlin upland; gravel concentration (grey tone) occurs on stoss, lateral and lee surfaces. Note drumline truncation (dt).



Figure 26. Drumlin terrace is indicated by a sculpted bank (SB) and concentration of rounded boulders in foreground; notebook (nb), 11 x17 cm for scale.



Figure 27. Stoss-side troughs form a series of arcuate, crescentic lakes (CL) that extend across multiple drumlins (d) flanked by furrows (f), terraces (t) and sculpted banks (SB); flow was toward the viewer.



Figure 28. Symmetric drumlin with scattered boulder cover; sculpted bank (SB) defines lateral drumlin depression; note sandy terrace on the downflow end of the drumlin; view is upflow to the west.



Figure 29. Stoss end of drumlin with upflow depression (lakes) in the background; note concentration of large, sub-rounded boulders; diamicton was sampled below the gravelly surface sediment.



Figure 30. Terrace gravel is predominantly rounded boulders with largest sub-angular clasts on drumlin flank; note boulder blanket over a 5-10 m elevation range.



Figure 31. Low relief drumlins (5-15m) form a truncated remnant upland (4 labeled drumlins, d) in wide corridor (dashed) adjacent to sandy esker (E) with narrow and broad segments (sandy); note eroded bedrock (R) next to esker; view and flow away from viewer to west.



Figure 32. Inter-drumlin sample site has thin sandy diamicton and surface gravel concentration; a typical sample pit in a corridor setting.



Figure 33. Example of a drumlin (d) formed by erosional processes displaying over 30 m of thick, horizontally-bedded sand with multi-level terraces (t) underlying thin diamicton on banks of the Mary Francis River; paleoflow was left to right.



Figure 34. Terrace gravel with predominant rounded to sub-rounded boulders; note sorting of coarser clasts to the higher (near side) of the terrace; terrace is set between two scoured rock uplands with scattered sub-rounded boulders; note person in white outfit for scale.



Figure 35. Large boulder with vegetated depression and no gravel in depression around the boulder; inferred to be a scour pit (dashed line); flow towards the viewer; notebook (11 x17 cm) for scale.



Figure 36. Channel (ch) eroded several drumlins (d), defined by a sculpted bank (SB) and a terrace (t) along a drumlin flank; note small sandy esker ridge to left of channel.



Figure 37. Gravel bar (gb) with larger clasts to right and smaller clasts to left (downflow).



Figure 38. Transverse ridges (TR), ~2-7 m high, ~10-15m wide and ~100-150 m long, often run perpendicular to the corridor long axis and adjacent to esker (E, light sandy ridges).

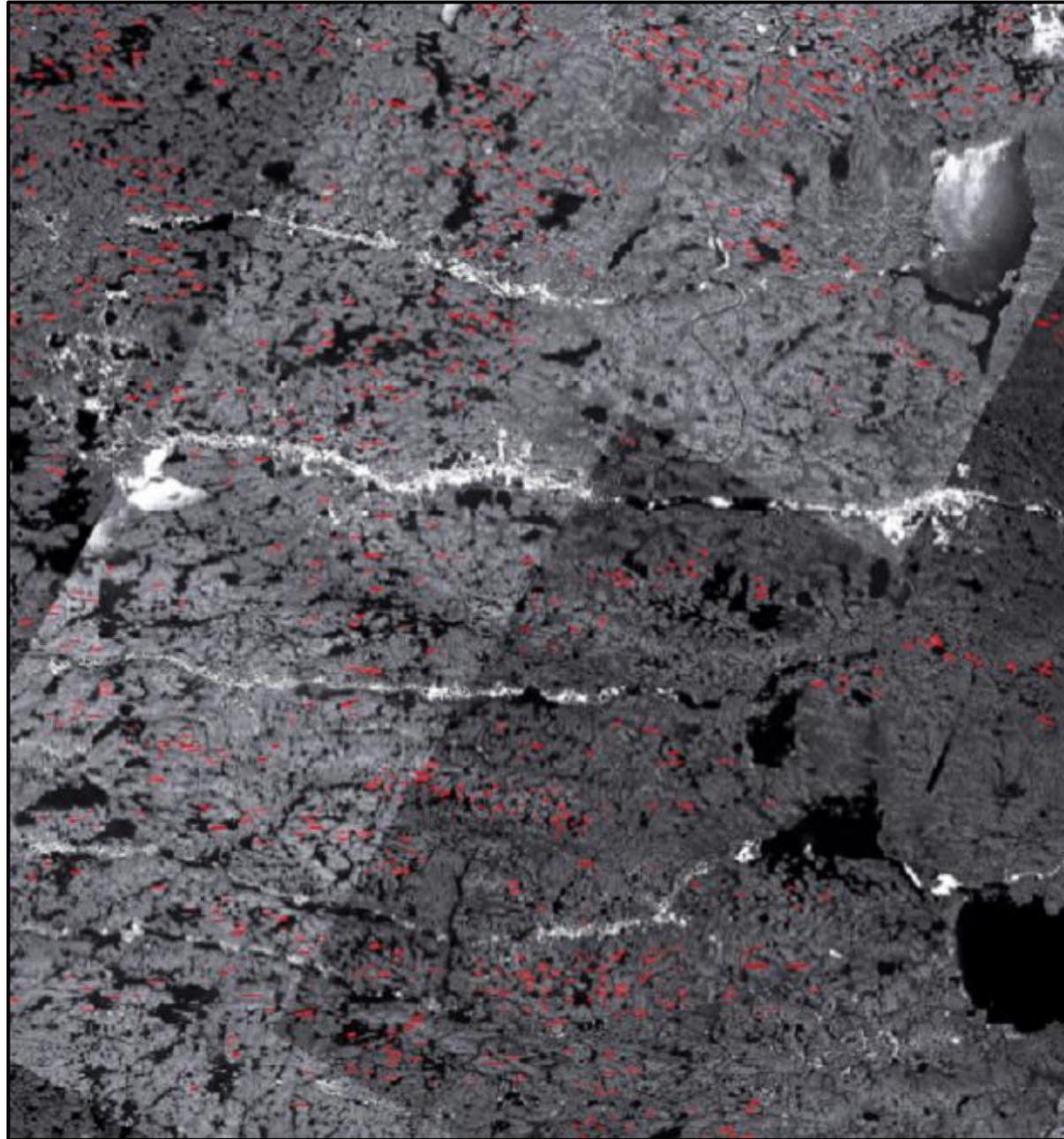


Figure 39. LANDSAT image of esker-drumlin pattern near the Thelon river (east central) shows eskers (white) trending east-west, ~8-12 km apart; width of scene is ~100 km; note white areas with sandy sediment have gaps (lakes) where erosion was prominent. Red symbols are drumlins.



Figure 40. Single crested, flat-topped esker ('railway embankment' type) with sandy aprons or fan (F) adjacent to esker ridge (E); note exposed bedrock (R) with scattered boulders adjacent to esker.



Figure 41. Complex array of esker types and morphologies, sharp-crested (e) transitional from flat-topped (f); note esker ridges and mounds apart from the main esker ridges; sand and gravel terraces (t) occur with eskers and below a sculpted bank (SB) on a drumlin, a possible corridor margin; note lateral sediment aprons (A) and hummocky surfaces (h).



Figure 42. Single-crested esker ridges consisting of undulating mounds; note gravel occurs along the sharp esker crestline.



Figure 43. Single-crested ridge (s) leading to multiple bifurcations and re-attachments in sandy rounded /flat-topped esker ridges (b); note sandy hummocks (h) apart from main ridges.



Figure 44. Esker ridge (E) and fan (F) complex, set within a poorly-defined corridor (C, dashed line at margin); not sculpted bank (SB) on drumlin within corridor.



Figure 45. Single-crested (e) and flat-topped esker with gravel terrace (gt) adjacent to esker ridges.



Figure 46. Esker complex with ridges (r) and hummocks (h) in a wide zone; note erosional banks on drumlin flanks in background (dashed line).



Figure 47. Multiple, concentric ridge lines, or terraces occur on some drumlins, in places with spit-like extremities as in the truncated sandy terrain near Thelon River.



Figure 48. Sub-rounded gravel clasts occur in organized forms or ridges on terrace surfaces.



Figure 49. Large, 30-50 m diameter polygons (p) on drumlin uplands; polygons are smaller and poorly formed on better-vegetated north facing slopes.



Figure 50. Solifluction (S) modification of the slopes of a drumlin with terraced flanks.



Figure 51. Diamicton sample site contains angular to sub-angular clasts in greater abundance on the surface compare to subsurface (see screen fraction from 70 cm pit); note mud-boils in sediment patches within brown vegetation.



Figure 52. Sample site with more stones on the surface (~5-10%) than are present within sampled diamicton pit <3%.



Figure 53. Striated volcanic and sandstone clasts weathered out of sandy diamicton atop river bluff, Mary Francis River (see figure 7m).



Figure 54. Sample pit shows a ~15cm thick reworked, sub-rounded gravel layer over ~25 cm of stone-poor, sandy, buff-coloured diamicton.